CHAPTER 10

Cellular Wireless Networks

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LEARNING OBJECTIVES

After reading this chapter, you should be able to:

- Provide an overview of cellular network organization.
- Distinguish among four generations of mobile telephony.
- Understand the relative merits of time-division multiple access (TDMA) and code division multiple access (CDMA) approaches to mobile telephony.
- Present an overview of LTE-Advanced.

Of all the tremendous advances in data communications and telecommunications, perhaps the most revolutionary is the development of **cellular networks**. Cellular technology is the foundation of mobile wireless communications and supports users in locations that are not easily served by wired networks. Cellular technology is the underlying technology for mobile telephones, personal communications systems, wireless Internet and wireless Web applications, and much more.

We begin this chapter with a look at the basic principles used in all cellular networks. Then we look at specific cellular technologies and standards, which are conveniently grouped into four generations. Finally, we examine LTE-Advanced, which is the standard for the fourth generation, in more detail.

10.1 PRINCIPLES OF CELLULAR NETWORKS

Cellular radio is a technique that was developed to increase the capacity available for mobile radio telephone service. Prior to the introduction of cellular radio, mobile radio telephone service was only provided by a high-power transmitter/receiver. A typical system would support about 25 channels with an effective radius of about 80 km. The way to increase the capacity of the system is to use lower-power systems with shorter radius and to use numerous transmitters/receivers.

Cellular Network Organization

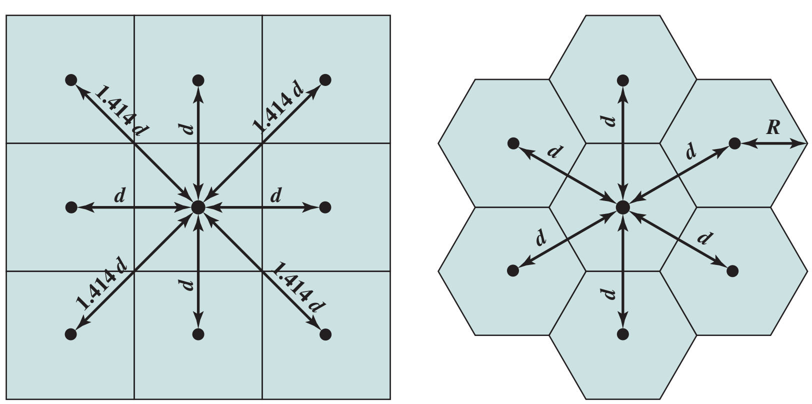
The essence of a cellular network is the use of multiple low-power transmitters, on the order of 100 W or less. Because the range of such a transmitter is small, an area can be divided into cells, each one served by its own antenna. Each cell is allocated a band of frequencies and is served by a **base station**, consisting of transmitter, receiver, and control unit. Adjacent cells are assigned different frequencies to avoid interference or crosstalk. However, cells sufficiently distant from each other can use the same frequency band.

The first design decision to make is the shape of cells to cover an area. A matrix of square cells would be the simplest layout to define (Figure 10.1a). However, this geometry is not ideal. If the width of a square cell is d, then a cell has four neighbors at a distance d and four neighbors at a distance $\sqrt{2}d$. As a mobile user within a cell moves toward the cell's boundaries, it is best if all of the adjacent antennas are equidistant. This simplifies the task of determining when to switch the user to an adjacent antenna and which antenna to choose. A hexagonal pattern provides for equidistant antennas (Figure 10.1b). The radius of a hexagon is defined to be the radius of the circle that circumscribes it (equivalently, the distance from the center to each vertex; also equal to the length of a side of a hexagon). For a cell radius R, the distance between the cell center and each adjacent cell center is $d = \sqrt{3}R$.

In practice, a precise hexagonal pattern is not used. Variations from the ideal are due to topographical limitations, local signal propagation conditions, and practical limitation on siting antennas.

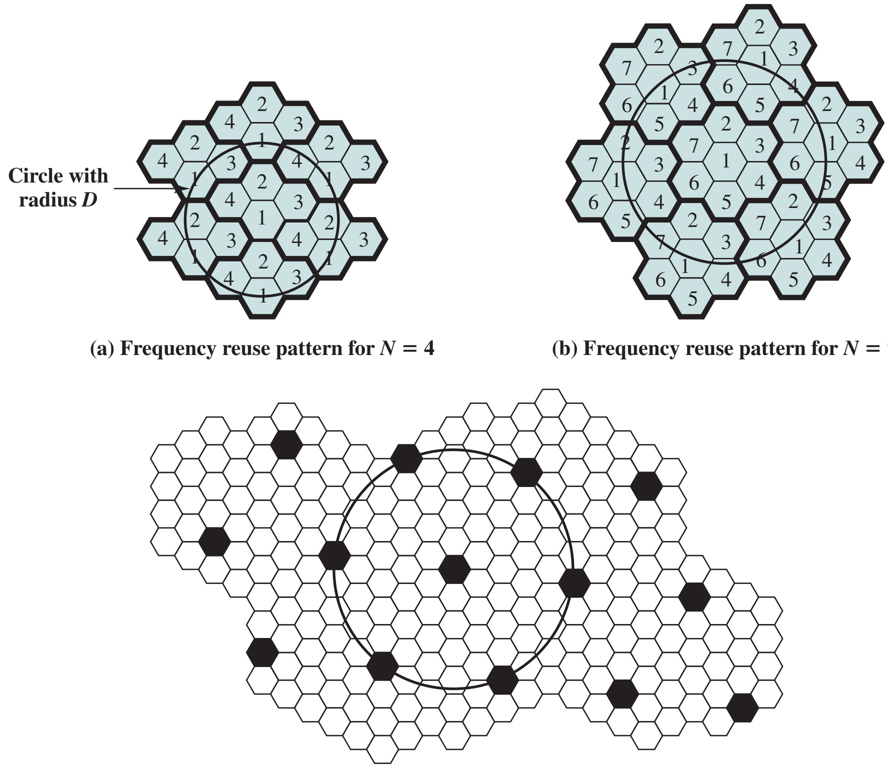
A wireless cellular system limits the opportunity to use the same frequency for different communications because the signals, not being constrained, can interfere with one another even if geographically separated. Systems supporting a large number of communications simultaneously need mechanisms to conserve spectrum.

Frequency Reuse In a cellular system, each cell has a base transceiver. The transmission power is carefully controlled (to the extent that it is possible in the highly variable mobile communication environment) to allow communication within the cell using a given frequency, while limiting the power at that frequency that escapes the cell into adjacent ones. The objective is to use the same frequency in other nearby (but not adjacent) cells, thus allowing the frequency to be used for multiple simultaneous conversations. Generally, 10 to 50 frequencies are assigned to each cell, depending on the traffic expected.



(a) Square pattern   (b) Hexagonal pattern

Figure 10.1 Cellular Geometries



(a) Frequency reuse pattern for $N = 4$

(b) Frequency reuse pattern for $N = 7$

(c) Black cells indicate a frequency reuse for $N = 19$

Figure 10.2 Frequency Reuse Patterns

The essential issue is to determine how many cells must intervene between two cells using the same frequency so that the two cells do not interfere with each other. Various patterns of frequency reuse are possible. Figure 10.2 shows some examples. If the pattern consists of N cells and each cell is assigned the same number of frequencies, each cell can have K/N frequencies, where K is the total number of frequencies allotted to the system.

In characterizing frequency reuse, the following parameters are commonly used:

D = minimum distance between centers of cells that use the same band of frequencies (called cochannels)

R = radius of a cell

d = distance between centers of adjacent cells ($d = \sqrt{3}R$)

N = number of cells in a repetitious pattern (each cell in the pattern uses a unique band of frequencies), termed the **reuse factor**

In a hexagonal cell pattern, only the following values of N are possible:

$$N = I^2 + J^2 + (I \times J) \quad I, J = 0, 1, 2, 3, \ldots$$

Hence, possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, and so on. The following relationship holds:

$$\frac{D}{R} = \sqrt{3N}$$

This can also be expressed as $D/d = \sqrt{N}$.

Increasing Capacity In time, as more customers use the system, traffic may build up so that there are not enough frequencies assigned to a cell to handle its calls. A number of approaches have been used to cope with this situation, including the following:

- **Adding new channels:** Typically, when a system is set up in a region, not all of the channels are used, and growth and expansion can be managed in an orderly fashion by adding new channels.
- **Frequency borrowing:** In the simplest case, frequencies are taken from adjacent cells by congested cells. The frequencies can also be assigned to cells dynamically.
- **Cell splitting:** In practice, the distribution of traffic and topographic features is not uniform, and this presents opportunities for capacity increase. Cells in areas of high usage can be split into smaller cells. Generally, the original cells are about 6.5 to 13 km in size. The smaller cells can themselves be split; however, 1.5-km cells are close to the practical minimum size as a general solution (but see the subsequent discussion of microcells). To use a smaller cell, the power level used must be reduced to keep the signal within the cell. Also, as the mobile units move, they pass from cell to cell, which requires transferring of the call from one base transceiver to another. This process is called a handoff. As the cells get smaller, these handoffs become much more frequent. Figure 10.3 indicates schematically how cells can be divided to provide more

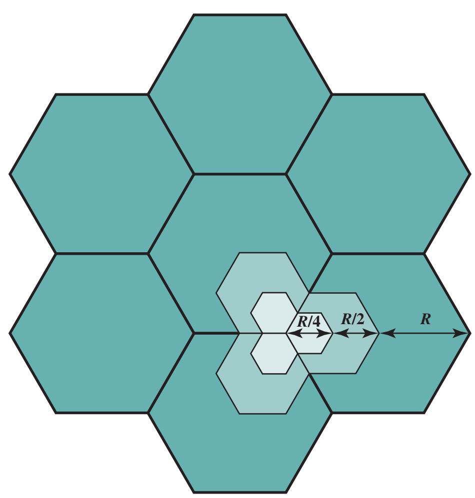


Figure 10.3 Cell Splitting with Cell Reduction Factor of $F = 2$

capacity. A radius reduction by a factor of F reduces the coverage area and increases the required number of base stations by a factor of F^2.

- **Cell sectoring:** With cell sectoring, a cell is divided into a number of wedge-shaped sectors, each with its own set of channels, typically three or six sectors per cell. Each sector is assigned a separate subset of the cell's channels, and directional antennas at the base station are used to focus on each sector.
- **Microcells:** As cells become smaller, antennas move from the tops of tall buildings or hills to the tops of small buildings or the sides of large buildings, and finally to lamp posts, where they form microcells. Each decrease in cell size is accompanied by a reduction in the radiated power levels from the base stations and the mobile units. Microcells are useful in city streets in congested areas, along highways, and inside large public buildings.

EXAMPLE 10.1 Assume a system of 32 cells with a cell radius of 1.6 km, a total frequency bandwidth that supports 336 traffic channels, and a reuse factor of $N = 7$. If there are 32 total cells, what geographic area is covered, how many channels are there per cell, and what is the total number of concurrent calls that can be handled? Repeat for a cell radius of 0.8 km and 128 cells.

Figure 10.4a shows an approximately square pattern. The area of a hexagon of radius R is $1.5R^2\sqrt{3}$. A hexagon of radius 1.6 km has an area of 6.65 km^2, and the total area covered is $6.65 \times 32 = 213\,\text{km}^2$. For $N = 7$, the number of channels per cell is $336/7 = 48$, for a total channel capacity of $48 \times 32 = 1536$ channels. For the layout of Figure 10.4b, the area covered is $1.66 \times 128 = 213\text{km}^2$. The number of channels per cell is $336/7 = 48$, for a total channel capacity of $48 \times 128 = 6144$ channels.

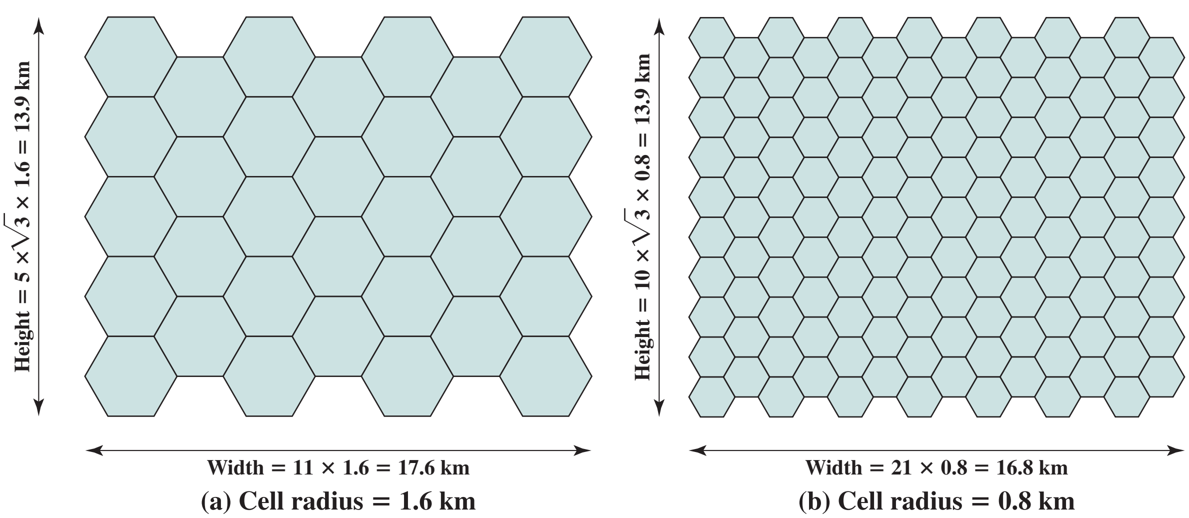


Figure 10.4 Frequency Reuse Example

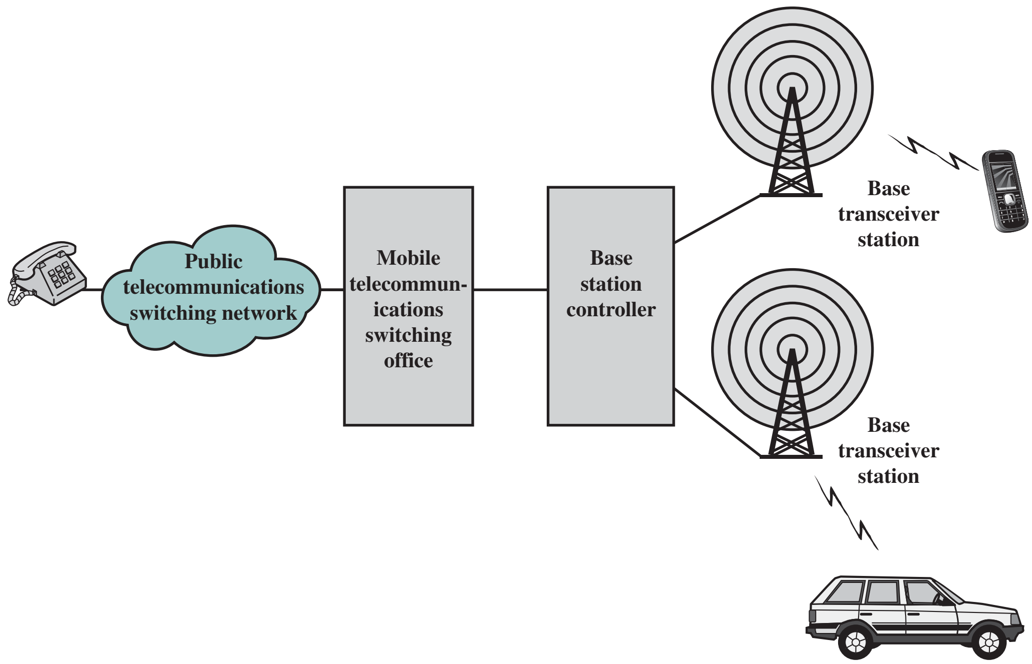


Figure 10.5 Overview of Cellular System

Operation of Cellular Systems

Figure 10.5 shows the principal elements of a cellular system. In the approximate center of each cell is a base station (BS). The BS includes one or more antennas, a controller, and a number of transceivers for communicating on the channels assigned to that cell. The controller is used to handle the call process between the mobile unit and the rest of the network. At any time, a number of mobile user units may be active and moving about within a cell, communicating with the BS. Each BS is connected to a mobile telecommunications switching office (MTSO), with one MTSO serving multiple BSs. Typically, the link between an MTSO and a BS is by a wire line, although a wireless link is also possible. The MTSO connects calls between mobile units. The MTSO is also connected to the public telephone or telecommunications network and can make a connection between a fixed subscriber to the public network and a mobile subscriber to the cellular network. The MTSO assigns the voice channel to each call, performs handoffs, and monitors the call for billing information.

The use of a cellular system is fully automated and requires no action on the part of the user other than placing or answering a call. Two types of channels are available between the mobile unit and the base station: control channels and traffic channels. **Control channels** are used to exchange information having to do with setting up and maintaining calls and with establishing a relationship between a mobile unit and the nearest BS. **Traffic channels** carry a voice or data connection between users. Figure 10.6 illustrates the steps in a typical call between two mobile users within an area controlled by a single MTSO:

- **Mobile unit initialization:** When the mobile unit is turned on, it scans and selects the strongest setup control channel used for this system (Figure 10.6a). Cells with different frequency bands repetitively broadcast on different setup channels. The receiver selects the strongest setup channel and monitors that channel. The effect of this procedure is that the mobile unit has automatically selected the BS antenna of the cell within which it will operate.[1] Then

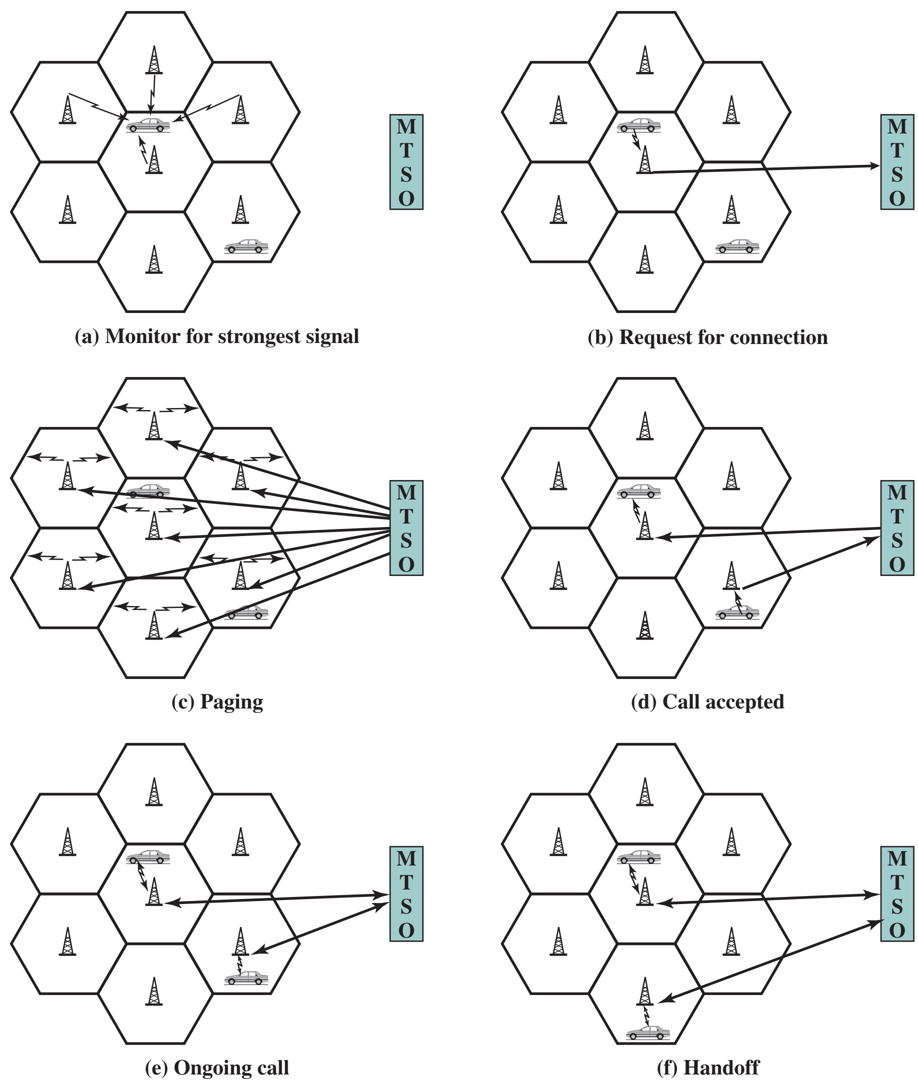


Figure 10.6 Example of Mobile Cellular Cell

[1]Usually, but not always, the antenna and therefore the base station selected is the closest one to the mobile unit. However, because of propagation anomalies, this is not always the case.

a handshake takes place between the mobile unit and the MTSO controlling this cell, through the BS in this cell. The handshake is used to identify the user and register its location. As long as the mobile unit is on, this scanning procedure is repeated periodically to account for the motion of the unit. If the unit enters a new cell, then a new BS is selected. In addition, the mobile unit is monitoring for pages, discussed subsequently.

- **Mobile-originated call:** A mobile unit originates a call by sending the number of the called unit on the preselected setup channel (Figure 10.6b). The receiver at the mobile unit first checks that the setup channel is idle by examining information in the forward (from the BS) channel. When an idle condition is detected, the mobile may transmit on the corresponding reverse (to BS) channel. The BS sends the request to the MTSO.
- **Paging:** The MTSO then attempts to complete the connection to the called unit. The MTSO sends a paging message to certain BSs depending on the called mobile number (Figure 10.6c). Each BS transmits the paging signal on its own assigned setup channel.
- **Call accepted:** The called mobile unit recognizes its number on the setup channel being monitored and responds to that BS, which sends the response to the MTSO. The MTSO sets up a circuit between the calling and called BSs. At the same time, the MTSO selects an available traffic channel within each BS's cell and notifies each BS, which in turn notifies its mobile unit (Figure 10.6d). The two mobile units tune to their respective assigned channels.
- **Ongoing call:** While the connection is maintained, the two mobile units exchange voice or data signals, going through their respective BSs and the MTSO (Figure 10.6e).
- **Handoff:** If a mobile unit moves out of range of one cell and into the range of another during a connection, the traffic channel has to change to one assigned to the BS in the new cell (Figure 10.6f). The system makes this change without either interrupting the call or alerting the user.

Other functions performed by the system but not illustrated in Figure 10.6 include the following:

- **Call blocking:** During the mobile-initiated call stage, if all the traffic channels assigned to the nearest BS are busy, then the mobile unit makes a preconfigured number of repeated attempts. After a certain number of failed tries, a busy tone is returned to the user.
- **Call termination:** When one of the two users hangs up, the MTSO is informed and the traffic channels at the two BSs are released.
- **Call drop:** During a connection, because of interference or weak signal spots in certain areas, if the BS cannot maintain the minimum required signal strength for a certain period of time, the traffic channel to the user is dropped and the MTSO is informed.
- **Calls to/from fixed and remote mobile subscriber:** The MTSO connects to the public switched telephone network. Thus, the MTSO can set up a connection

between a mobile user in its area and a fixed subscriber via the telephone network. Further, the MTSO can connect to a remote MTSO via the telephone network or via dedicated lines and set up a connection between a mobile user in its area and a remote mobile user.

Mobile Radio Propagation Effects

Mobile radio communication introduces complexities not found in wire communication or in fixed wireless communication. Two general areas of concern are signal strength and signal propagation effects.

- **Signal strength:** The strength of the signal between the base station and the mobile unit must be strong enough to maintain signal quality at the receiver but not so strong as to create too much cochannel interference with channels in another cell using the same frequency band. Several complicating factors exist. Human-made noise varies considerably, resulting in a variable noise level. For example, automobile ignition noise in the cellular frequency range is greater in the city than in a suburban area. Other signal sources vary from place to place. The signal strength varies as a function of distance from the BS to a point within its cell. Moreover, the signal strength varies dynamically as the mobile unit moves.
- **Fading**: Even if signal strength is within an effective range, signal propagation effects may disrupt the signal and cause errors. Fading is discussed subsequently in this section.

In designing a cellular layout, the communications engineer must take account of these various propagation effects, the desired maximum transmit power level at the base station and the mobile units, the typical height of the mobile unit antenna, and the available height of the BS antenna. These factors will determine the size of the individual cell. Unfortunately, as just described, the propagation effects are dynamic and difficult to predict. The best that can be done is to come up with a model based on empirical data and to apply that model to a given environment to develop guidelines for cell size. One of the most widely used models was developed by Okumura et al. [OKUM68] and subsequently refined by Hata [HATA80]. The original was a detailed analysis of the Tokyo area and produced path loss information for an urban environment. Hata's model is an empirical formulation that takes into account a variety of environments and conditions. For an urban environment, predicted path loss is

$$L_{dB} = 69.55 + 26.16 \log f_c - 13.82 \log h_t - \mathrm{A}(h_r) + (44.9 - 6.55 \log h_t) \log d \quad \textbf{(10.1)}$$

where

f_c = carrier frequency in MHz from 150 to 1500 MHz
h_t = height of transmitting antenna (base station) in m, from 30 to 300 m
h_r = height of receiving antenna (mobile station) in m, from 1 to 10 m
d = propagation distance between antennas in km, from 1 to 20 km
$\mathrm{A}(h_r)$ = correction factor for mobile antenna height

For a small- or medium-sized city, the correction factor is given by

$$A(h_r) = (1.1 \log f_c - 0.7)\, h_r - (1.56 \log f_c - 0.8) \text{ dB}$$

And for a large city it is given by

$$A(h_r) = 8.29\,[\log(1.54\, h_r)]^2 - 1.1 \text{ dB} \qquad \text{for } f_c \leq 300 \text{ MHz}$$
$$A(h_r) = 3.2\,[\log(11.75\, h_r)]^2 - 4.97 \text{ dB} \qquad \text{for } f_c \geq 300 \text{ MHz}$$

To estimate the path loss in a suburban area, the formula for urban path loss in Equation (10.1) is modified as:

$$L_{\text{dB}}(\text{suburban}) = L_{\text{dB}}(\text{urban}) - 2[\log(f_c/28)]^2 - 5.4$$

And for the path loss in open areas, the formula is modified as

$$L_{\text{dB}}(\text{open}) = L_{\text{dB}}(\text{urban}) - 4.78(\log f_c)^2 - 18.733\,(\log f_c) - 40.98$$

The Okumura/Hata model is considered to be among the best in terms of accuracy in path loss prediction and provides a practical means of estimating path loss in a wide variety of situations [FREE07].

EXAMPLE 10.2 Let $f_c = 900$ MHz, $h_t = 40$ m, $h_r = 5$ m, and $d = 10$ km. Estimate the path loss for a medium-size city.

$$A(h_r) = (1.1 \log 900 - 0.7)\,5 - (1.56 \log 900 - 0.8) \text{ dB}$$
$$= 12.75 - 3.8 = 8.95 \text{ dB}$$

$$L_{\text{dB}} = 69.55 + 26.16 \log 900 - 13.82 \log 40 - 8.95 + (44.9 - 6.55 \log 40) \log 10$$
$$= 69.55 + 77.28 - 22.14 - 8.95 + 34.4 = 150.14 \text{ dB}$$

Fading in the Mobile Environment

Perhaps the most challenging technical problem facing communications systems engineers is fading in a mobile environment. The term *fading* refers to the time variation of received signal power caused by changes in the transmission medium or path(s). In a fixed environment, fading is affected by changes in atmospheric conditions, such as rainfall. But in a mobile environment, where one of the two antennas is moving relative to the other, the relative location of various obstacles changes over time, creating complex transmission effects.

Multipath Propagation Three propagation mechanisms, illustrated in Figure 10.7, play a role. **Reflection** occurs when an electromagnetic signal encounters a surface that is large relative to the wavelength of the signal. For example, suppose a ground-reflected wave near the mobile unit is received. Because the ground-reflected wave has a 180° phase shift after reflection, the ground wave and the line-of-sight (LOS) wave may tend to cancel, resulting in high signal loss.[2] Further, because the mobile antenna is lower than most human-made structures in the area, multipath

[2]On the other hand, the reflected signal has a longer path, which creates a phase shift due to delay relative to the unreflected signal. When this delay is equivalent to half a wavelength, the two signals are back in phase.

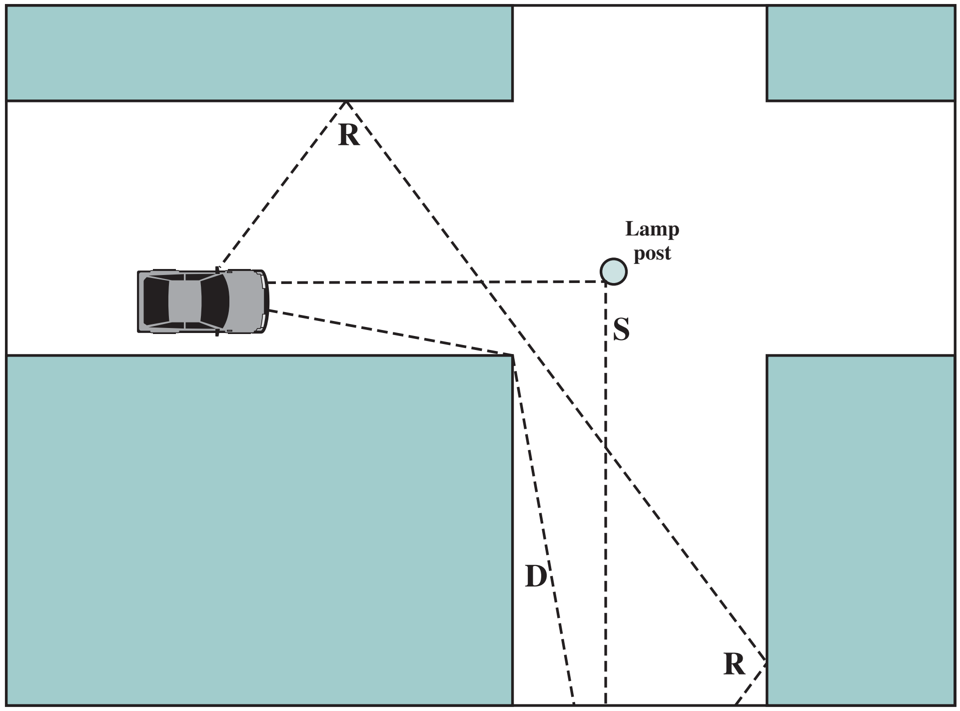


Figure 10.7 Sketch of Three Important Propagation Mechanisms: Reflection (R), Scattering (S), Diffraction (D) [ANDE95]

interference occurs. These reflected waves may interfere constructively or destructively at the receiver.

Diffraction occurs at the edge of an impenetrable body that is large compared to the wavelength of the radio wave. When a radio wave encounters such an edge, waves propagate in different directions with the edge as the source. Thus, signals can be received even when there is no unobstructed LOS from the transmitter.

If the size of an obstacle is on the order of the wavelength of the signal or less, **scattering** occurs. An incoming signal is scattered into several weaker outgoing signals. At typical cellular microwave frequencies, there are numerous objects, such as lamp posts and traffic signs, that can cause scattering. Thus, scattering effects are difficult to predict.

These three propagation effects influence system performance in various ways depending on local conditions and as the mobile unit moves within a cell. If a mobile unit has a clear LOS to the transmitter, then diffraction and scattering are generally minor effects, although reflection may have a significant impact. If there is no clear LOS, such as in an urban area at street level, then diffraction and scattering are the primary means of signal reception.

The Effects of Multipath Propagation As just noted, one unwanted effect of multipath propagation is that multiple copies of a signal may arrive at different phases. If these phases add destructively, the signal level relative to noise declines, making signal detection at the receiver more difficult.

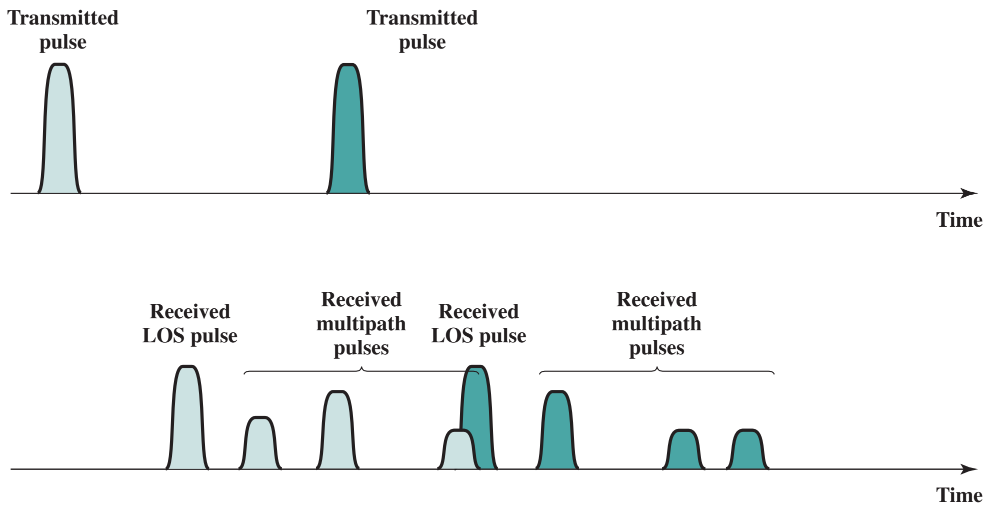


Figure 10.8 Two Pulses in Time-Variant Multipath

A second phenomenon, of particular importance for digital transmission, is intersymbol interference (ISI). Consider that we are sending a narrow pulse at a given frequency across a link between a fixed antenna and a mobile unit. Figure 10.8 shows what the channel may deliver to the receiver if the impulse is sent at two different times. The upper line shows two pulses at the time of transmission. The lower line shows the resulting pulses at the receiver. In each case the first received pulse is the desired LOS signal. The magnitude of that pulse may change because of changes in atmospheric attenuation. Further, as the mobile unit moves farther away from the fixed antenna, the amount of LOS attenuation increases. But in addition to this primary pulse, there may be multiple secondary pulses due to reflection, diffraction, and scattering. Now suppose that this pulse encodes one or more bits of data. In that case, one or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit. These delayed pulses act as a form of noise to the subsequent primary pulse, making recovery of the bit information more difficult.

As the mobile antenna moves, the location of various obstacles changes; hence the number, magnitude, and timing of the secondary pulses change. This makes it difficult to design signal-processing techniques that will filter out multipath effects so that the intended signal is recovered with fidelity.

Types of Fading Fading effects in a mobile environment can be classified as either fast or slow. Referring to Figure 10.7, as the mobile unit moves down a street in an urban environment, rapid variations in signal strength occur over distances of about one-half a wavelength. At a frequency of 900 MHz, which is typical for mobile cellular applications, the wavelength is 0.33 m. Changes of amplitude can be as much as 20 or 30 dB over a short distance. This type of rapidly changing fading phenomenon, known as **fast fading**, affects not only mobile phones in automobiles, but even a mobile phone user walking down an urban street.

As the mobile user covers distances well in excess of a wavelength, the urban environment changes, as the user passes buildings of different heights, vacant lots, intersections, and so forth. Over these longer distances, there is a change in the average received power level about which the rapid fluctuations occur. This is referred to as **slow fading**.

Fading effects can also be classified as flat or selective. **Flat fading**, or nonselective fading, is that type of fading in which all frequency components of the received signal fluctuate in the same proportions simultaneously. **Selective fading** affects unequally the different spectral components of a radio signal. The term *selective fading* is usually significant only relative to the bandwidth of the overall communications channel. If attenuation occurs over a portion of the bandwidth of the signal, the fading is considered to be selective; nonselective fading implies that the signal bandwidth of interest is narrower than, and completely covered by, the spectrum affected by the fading.

Error Compensation Mechanisms The efforts to compensate for the errors and distortions introduced by multipath fading fall into three general categories: forward error correction, adaptive equalization, and diversity techniques. In the typical mobile wireless environment, techniques from all three categories are combined to combat the error rates encountered.

Forward error correction is applicable in digital transmission applications: those in which the transmitted signal carries digital data or digitized voice or video data. Typically in mobile wireless applications, the ratio of total bits sent to data bits sent is between 2 and 3. This may seem an extravagant amount of overhead, in that the capacity of the system is cut to one-half or one-third of its potential, but the mobile wireless environment is so difficult that such levels of redundancy are necessary. Chapter 6 discusses forward error correction.

Adaptive equalization can be applied to transmissions that carry analog information (e.g., analog voice or video) or digital information (e.g., digital data, digitized voice or video) and is used to combat intersymbol interference. The process of equalization involves some method of gathering the dispersed symbol energy back together into its original time interval. Equalization is a broad topic; techniques include the use of so-called lumped analog circuits as well as sophisticated digital signal processing algorithms.

Diversity is based on the fact that individual channels experience independent fading events. We can therefore compensate for error effects by providing multiple logical channels in some sense between transmitter and receiver and sending part of the signal over each channel. This technique does not eliminate errors but it does reduce the error rate, since we have spread the transmission out to avoid being subjected to the highest error rate that might occur. The other techniques (equalization, forward error correction) can then cope with the reduced error rate.

Some diversity techniques involve the physical transmission path and are referred to as **space diversity**. For example, multiple nearby antennas may be used to receive the message, with the signals combined in some fashion to reconstruct the most likely transmitted signal. Another example is the use of collocated multiple directional antennas, each oriented to a different reception angle with the incoming signals again combined to reconstitute the transmitted signal.

More commonly, the term *diversity* refers to frequency diversity or time diversity techniques. With **frequency diversity**, the signal is spread out over a larger-frequency bandwidth or carried on multiple frequency carriers. The most important example of this approach is spread spectrum, which is examined in Chapter 17.

10.2 CELLULAR NETWORK GENERATIONS

Since their introduction in the mid-1980s, cellular networks have evolved rapidly. For convenience, industry and standards bodies group the technical advances into "generations." We are now up to the fourth generation (4G) of cellular network technology. In this section, we give a brief overview of the four generations. The following section is devoted to 4G.

Table 10.1 lists some of the key characteristics of the cellular network generations.

First Generation

The original cellular networks, now dubbed 1G, provided analog traffic channels and were designed to be an extension of the public switched telephone networks. Users with brick-sized cell phones placed and received calls in the same fashion as landline subscribers.

The most widely deployed 1G system was the **Advanced Mobile Phone Service (AMPS)**, developed by AT&T. This approach was also common in South America, Australia, and China.

In North America, two 25-MHz bands were allocated to AMPS, one for transmission from the base station to the mobile unit (869–894 MHz) and the other for transmission from the mobile to the base station (824–849 MHz). Each of these bands is split in two to encourage competition (i.e., in each market two operators can be accommodated). An operator is allocated only 12.5 MHz in each direction for its system. The channels are spaced 30 kHz apart, which allows a total of 416 channels per operator. Twenty-one channels are allocated for control, leaving 395 to carry calls. The control channels are data channels operating at 10 kbps. The conversation

Table 10.1 Wireless Network Generations

Technology	1G	2G	2.5G	4G
Design began	1970	1980	1985	2000
Implementation	1984	1991	1999	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	IP backbone

channels carry the conversations in analog using frequency modulation (FM). Simple FDMA is used to provide multiple access. Control information is also sent on the conversation channels in bursts as data. This number of channels is inadequate for most major markets, so some way must be found either to use less bandwidth per conversation or to reuse frequencies. Both approaches have been taken in the various approaches to 1G telephony. For AMPS, frequency reuse is exploited.

Second Generation

First-generation cellular networks, such as AMPS, quickly became highly popular, threatening to swamp available capacity. Second-generation systems (2G) were developed to provide higher-quality signals, higher data rates for support of digital services, and greater capacity. Key differences between 1G and 2G networks include:

- **Digital traffic channels:** The most notable difference between the two generations is that 1G systems are almost purely analog, whereas 2G systems are digital. In particular, 1G systems are designed to support voice channels using FM; digital traffic is supported only by the use of a modem that converts the digital data into analog form. 2G systems provide digital traffic channels. These systems readily support digital data; voice traffic is first encoded in digital form before transmitting.
- **Encryption:** Because all of the user traffic, as well as control traffic, is digitized in 2G systems, it is a relatively simple matter to encrypt all of the traffic to prevent eavesdropping. All 2G systems provide this capability, whereas 1G systems send user traffic in the clear, providing no security.
- **Error detection and correction:** The digital traffic stream of 2G systems also lends itself to the use of error detection and correction techniques, such as those discussed in Chapters 6 and 16. The result can be very clear voice reception.
- **Channel access:** In 1G systems, each cell supports a number of channels. At any given time a channel is allocated to only one user. 2G systems also provide multiple channels per cell, but each channel is dynamically shared by a number of users using TDMA (time-division multiple access) or CDMA (**code division multiple access**).

Third Generation

The objective of the third generation (3G) of wireless communication is to provide fairly high-speed wireless communications to support multimedia, data, and video in addition to voice. The ITU's International Mobile Telecommunications for the year 2000 (IMT-2000) initiative has defined the third-generation capabilities as follows:

- Voice quality comparable to the public switched telephone network
- 144 kbps data rate available to users in high-speed motor vehicles over large areas
- 384 kbps available to pedestrians standing or moving slowly over small areas
- Support (to be phased in) for 2.048 Mbps for office use

- Symmetrical and asymmetrical data transmission rates
- Support for both packet-switched and circuit-switched data services
- An adaptive interface to the Internet to reflect efficiently the common asymmetry between inbound and outbound traffic
- More efficient use of the available spectrum in general
- Support for a wide variety of mobile equipment
- Flexibility to allow the introduction of new services and technologies

The dominant technology for 3G systems is CDMA. Although three different CDMA schemes have been adopted, they share the following design features:

- **Bandwidth:** An important design goal for all 3G systems is to limit channel usage to 5 MHz. There are several reasons for this goal. On the one hand, a bandwidth of 5 MHz or more improves the receiver's ability to resolve multipath when compared to narrower bandwidths. On the other hand, available spectrum is limited by competing needs, and 5 MHz is a reasonable upper limit on what can be allocated for 3G. Finally, 5 MHz is adequate for supporting data rates of 144 and 384 kHz, the main targets for 3G services.
- **Chip rate:** Given the bandwidth, the chip rate depends on desired data rate, the need for error control, and bandwidth limitations. A chip rate of 3 Mcps or more is reasonable given these design parameters.
- **Multirate:** The term *multirate* refers to the provision of multiple fixed-data-rate logical channels to a given user, in which different data rates are provided on different logical channels. Further, the traffic on each logical channel can be switched independently through the wireless and fixed networks to different destinations. The advantage of multirate is that the system can flexibly support multiple simultaneous applications from a given user and can efficiently use available capacity by only providing the capacity required for each service.

Fourth Generation

The evolution of smartphones and cellular networks has ushered in a new generation of capabilities and standards, which is collectively called 4G. 4G systems provide ultra-broadband Internet access for a variety of mobile devices including laptops, smartphones, and tablets. 4G networks support Mobile Web access and high-bandwidth applications such as high-definition mobile TV, mobile video conferencing, and gaming services.

These requirements have led to the development of a fourth generation (4G) of mobile wireless technology that is designed to maximize bandwidth and throughput while also maximizing spectral efficiency. The ITU has issued directives for 4G networks. According to the ITU, an IMT-Advanced (or 4G) cellular system must fulfill a number of minimum requirements, including the following:

- Be based on an all-IP packet switched network.
- Support peak data rates of up to approximately 100 Mbps for high-mobility mobile access and up to approximately 1 Gbps for low-mobility access such as local wireless access.

- Dynamically share and use the network resources to support more simultaneous users per cell.
- Support smooth handovers across heterogeneous networks.
- Support high quality of service for next-generation multimedia applications.

In contrast to earlier generations, 4G systems do not support traditional circuit-switched telephony service, providing only IP telephony services. And, as may be observed in Table 10.1, the spread spectrum radio technologies that characterized 3G systems are replaced in 4G systems by OFDMA (orthogonal frequency-division multiple access) multicarrier transmission and frequency-domain equalization schemes.

Figure 10.9 illustrates several major differences between 3G and 4G cellular networks. As shown in Figure 10.9a, the connections between base stations and switching offices in 3G networks are typically cable-based, either copper or fiber wires. Circuit switching is supported to enable voice connections between mobile users and phones connected to the PSTN. Internet access in 3G networks may also be routed through switching offices. By contrast, in 4G networks, IP telephony is the norm as are IP packet-switched connections for Internet access. These are enabled by wireless connections, such as fixed broadband wireless access (BWA)

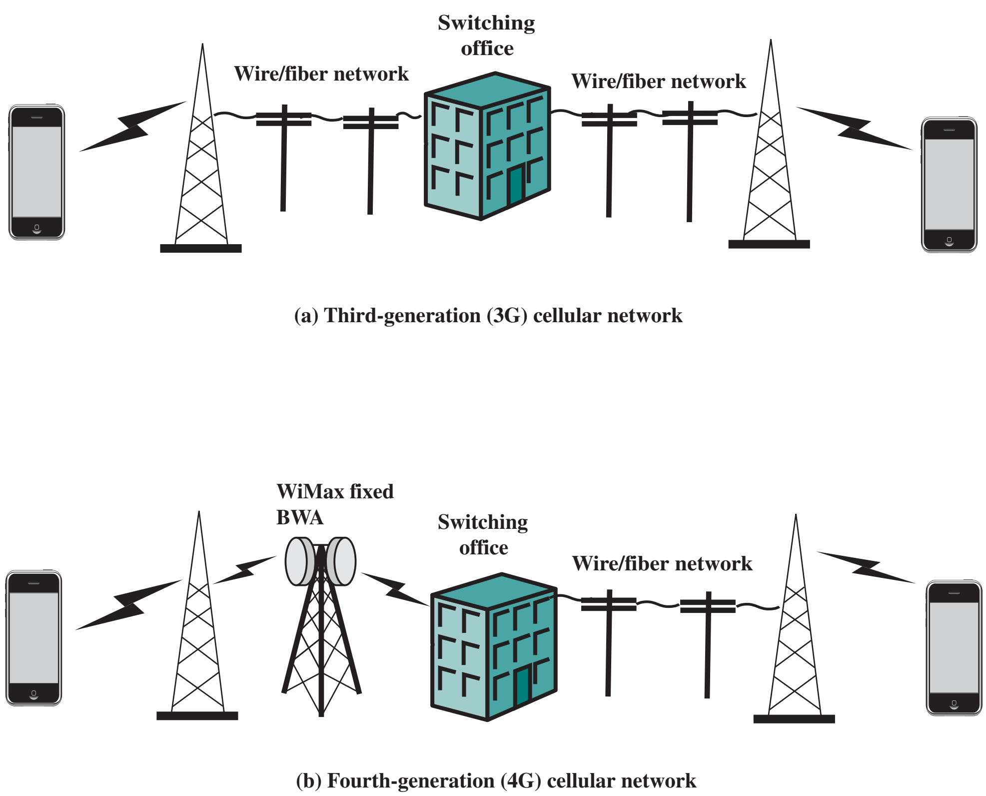


Figure 10.9 Third vs. Fourth Generation Cellular Networks

WiMAX, between base stations and switching offices (Figure 10.9b). Connections among mobile users with 4G-capable smartphones may never be routed over cable-based, circuit-switched connections—all communications between them can be IP-based and handled by wireless links. This setup facilitates deployment of mobile-to-mobile video call/video conferencing services and the simultaneous delivery of voice and data services (such as Web browsing while engaged in a phone call). 4G mobile users can still connect with 3G network users and PSTN subscribers over cable/fiber circuit-switched connections between the switching offices.

10.3 LTE-ADVANCED

Two candidates emerged for 4G standardization. One is known as **Long Term Evolution (LTE)**, which has been developed by the Third Generation Partnership Project (3GPP), a consortium of Asian, European, and North American telecommunications standards organizations. The other effort is from the IEEE 802.16 committee, which has developed standards for high-speed fixed wireless operations known as WiMAX (described in Chapter 18). The committee has specified an enhancement of WiMAX to meet 4G needs. The two efforts are similar in terms of both performance and technology. Both are based on the use of orthogonal frequency-division multiple access (OFDMA) to support multiple access to network resources. WiMAX uses a pure OFDMA approach for both uplink (UL) and downlink (DL). LTE uses pure OFDMA on the downlink and a technique that is based on OFDMA but offers enhanced power efficiency for the uplink. While WiMAX retains a role as the technology for fixed broadband wireless access, LTE has become the universal standard for 4G wireless. For example, all of the major carriers in the United States, including AT&T and Verizon, have adopted a version of LTE based on **frequency-division duplex (FDD)**, whereas China Mobile, the world's largest telecommunication carrier, has adopted a version of LTE based on time-division duplex (TDD).

LTE development began in the 3G era and its initial releases provided 3G or enhanced 3G services. Beginning with release 10, LTE provides a 4G service, known as **LTE-Advanced**. Table 10.2 compares the performance goals of LTE and LTE-Advanced.

Table 10.2 Comparison of Performance Requirements for LTE and LTE-Advanced

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	<50 ms
	Dormant to active	<50 ms	<10 ms
User plane delay		<5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350–500 km/h

The specification for LTE-Advanced is immense. This section provides a brief overview.

LTE-Advanced Architecture

Figure 10.10 illustrates the principal elements in an LTE-Advanced network. The heart of the system is the base station, designated **evolved NodeB (eNodeB)**. In LTE, the base station is referred to as NodeB. The key differences between the two base station technologies are:

- The NodeB station interface with subscriber stations (referred to as user equipment (UE)) is based on CDMA, whereas the eNodeB air interface is based on OFDMA.
- eNodeB embeds its own control functionality, rather than using an RNC (Radio Network Controller) as does a NodeB.

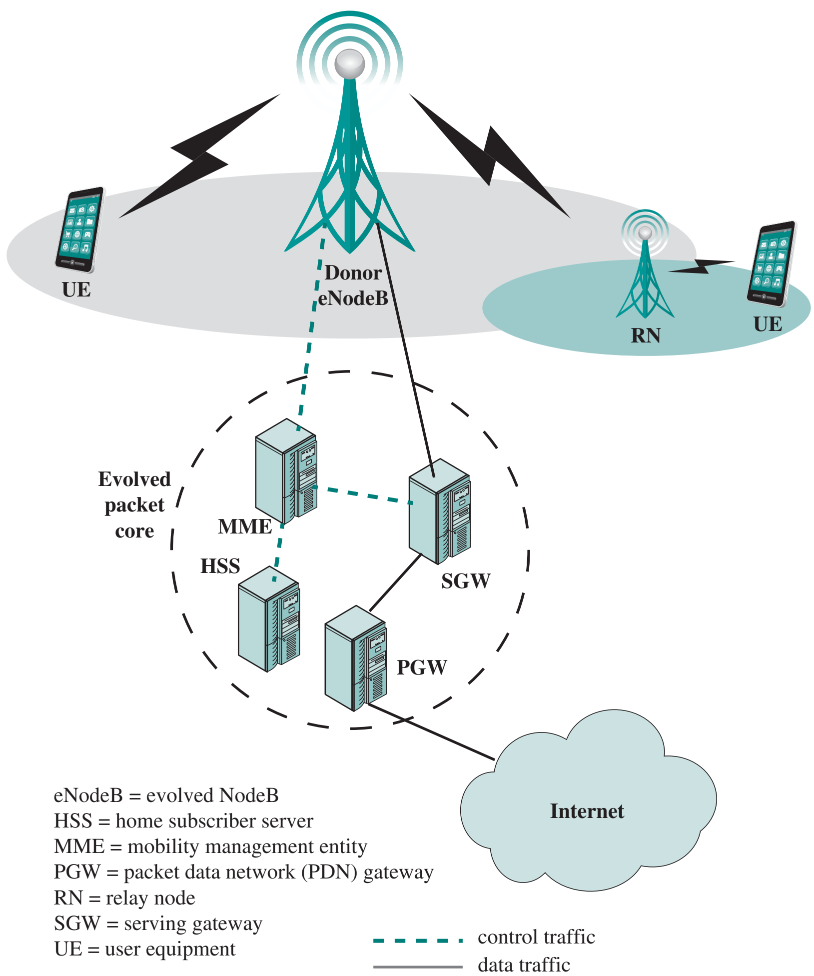


Figure 10.10 LTE-Advanced Configuration Elements

Relaying Another key element of an LTE-Advanced cellular network is the use of **relay nodes (RNs)**. As with any cellular system, an LTE-Advanced base station experiences reduced data rates near the edge of its cell, due to lower signal levels and higher interference levels. Rather than use smaller cells, it is more efficient to use small relay nodes, which have a reduced radius of operation compared to an eNodeB, distributed around the periphery of the cell. A UE near an RN communicates with the RN, which in turn communicates with the eNodeB.

An RN is not simply a signal repeater. Instead the RN receives, demodulates, and decodes the data and applies error correction as needed, and then transmits a new signal to the base station, referred to in this context as a **donor eNodeB**. The RN functions as a base station with respect to its communication with the UE and as a UE with respect to its communication with the eNodeB.

- The eNodeB → RN transmissions and RN → eNodeB transmissions are carried out in the DL frequency band and UL frequency band, respectively, for FDD systems.
- The eNodeB → RN transmissions and RN → eNodeB transmissions are carried out in the DL subframes of the eNodeB and RN and UL subframes of the eNodeB and RN, respectively, for TDD systems.

Currently, RNs use inband communication, meaning that the RN–eNodeB interface uses the same carrier frequency as the RN–UE interface. This creates an interference issue that can be described as follows. If the RN receives from the eNodeB and transmits to the UE at the same time, it is both transmitting and receiving on the downlink channel. The RN's transmission will have a much greater signal strength than the DL signal arriving from the eNodeB, making it very difficult to recover the incoming DL signal. The same problem occurs in the uplink direction. To overcome this difficulty, frequency resources are partitioned as follows:

- eNodeB → RN and RN → UE links are time-division multiplexed in a single frequency band and only one is active at any one time.
- RN → eNodeB and UE → RN links are time-division multiplexed in a single frequency band and only one is active at any one time.

Evolved Packet Core The operator, or carrier, network that interconnects all of the base stations of the carrier is referred to as the **evolved packet core (EPC)**. Traditionally, the core cellular network was circuit switched, but for 4G the core is entirely packet switched. It is based on IP and supports voice connections using voice over IP (VoIP).

Figure 10.10 illustrates the essential components of the EPC:

- **Mobility management entity (MME):** The MME deals with control signaling related to mobility and security. The MME is responsible for the tracking and the paging of UEs in idle-mode.
- **Serving gateway (SGW):** The SGW deals with user data transmitted and received by UEs in packet form, using IP. The SGW is the point of interconnect

between the radio side and the EPC. As its name indicates, this gateway serves the UE by routing the incoming and outgoing IP packets. It is the anchor point for the intra-LTE mobility (i.e., in case of handover between eNodeBs). Thus, packets can be routed from an eNodeB to an eNodeB in another area via the SGW, and can also be routed to external networks such as the Internet (via the PGW).

- **Packet data network gateway (PGW):** The PGW is the point of interconnect between the EPC and external IP networks such as the Internet. The PGW routes packets to and from the external networks. It also performs various functions such as IP address/IP prefix allocation and policy control and charging.
- **Home subscriber server (HSS):** The HSS maintains a database that contains user-related and subscriber-related information. It also provides support functions in mobility management, call and session setup, user authentication, and access authorization.

Figure 10.10 shows only a single instance of each configuration element. There are, of course, multiple eNodeBs, and multiple instances of each of the EPC elements. And there are many-to-many links between eNodeBs and MMEs, between MMEs and SGWs, and between SGWs and PGWs.

Femtocells Industry has responded to the increasing data transmission demands from smartphones, tablets, and similar devices by the introduction of 3G and now 4G cellular networks. As demand continues to increase, it becomes increasingly difficult to satisfy this requirement, particularly in densely populated areas and remote rural areas. An essential component of the 4G strategy for satisfying demand is the use of femtocells.

A **femtocell** is a low-power, short range, self-contained base station. Initially used to describe consumer units intended for residential homes, the term has expanded to encompass higher capacity units for enterprise, rural and metropolitan areas. Key attributes include IP backhaul, self-optimization, low power consumption, and ease of deployment. Femtocells are by far the most numerous type of small cells. The term *small cell* is an umbrella term for low-powered radio access nodes that operate in licensed and unlicensed spectrum that have a range of 10 m to several hundred meters. These contrast with a typical mobile macrocell, which might have a range of up to several tens of kilometers. Femtocells now outnumber macrocells, and the proportion of femtocells in 4G networks is expected to rise.

Figure 10.11 shows the typical elements in a network that uses femtocells. The femtocell access point is a small base station, much like a Wi-Fi hot spot base station, placed in a residential, business, or public setting. It operates in the same frequency band and with the same protocols as an ordinary cellular network base station. Thus, a 4G smartphone or tablet can connect wirelessly with a 4G femtocell with no change. The femtocell connects to the Internet, typically over a DSL, fiber, or cable landline. Packetized traffic to and from the femtocell connects to the cellular operator's core packet network via a femtocell gateway.

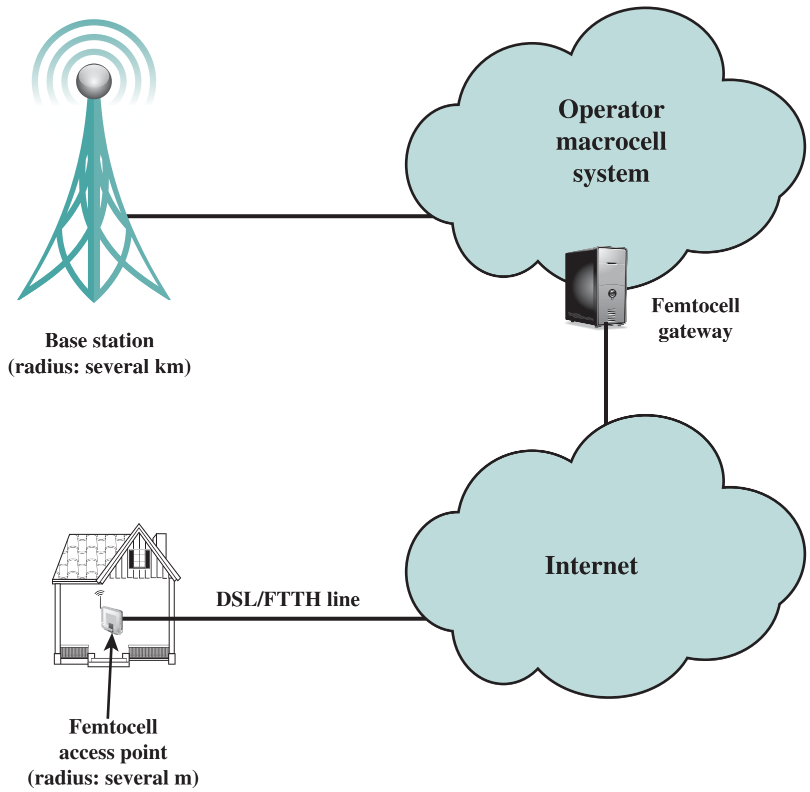


Figure 10.11 The Role of Femtocells

LTE-Advanced Transmission Characteristics

LTE-Advanced relies on two key technologies to achieve high data rates and spectral efficiency: orthogonal frequency-division multiplexing (OFDM) and multiple-input multiple-output (MIMO) antennas. Both of these technologies are explored in Chapter 17.

For the downlink, LTE-Advanced uses OFDMA and for the uplink SC-OFDM (single-carrier OFDM).

OFDM signals have a high peak-to-average power ratio (PAPR), requiring a linear power amplifier with overall low efficiency. This is a poor quality for battery-operated handsets. While complex, SC-FDMA has a lower PAPR and is better suited to portable implementation.

FDD and TDD LTE-Advanced has been defined to accommodate both paired spectrum for frequency-division duplex and unpaired spectrum for time-division duplex operation. Both LTE TDD and LTE FDD are being widely deployed as each form of the LTE standard has its own advantages and disadvantages. Table 10.3 compares key characteristics of the two approaches.

FDD systems allocate different frequency bands for uplink and downlink transmissions. The UL and DL channels are usually grouped into two blocks of contiguous

Table 10.3 Characteristics of TDD and FDD for LTE-Advanced

Parameter	LTE-TDD	LTE-FDD
Paired spectrum	Does not require paired spectrum as both transmit and receive occur on the same channel.	Requires paired spectrum with sufficient frequency separation to allow simultaneous transmission and reception.
Hardware cost	Lower cost as no diplexer is needed to isolate the transmitter and receiver. As cost of the UEs is of major importance because of the vast numbers that are produced, this is a key aspect.	Diplexer is needed and cost is higher.
Channel reciprocity	Channel propagation is the same in both directions which enables transmit and receive to use one set of parameters.	Channel characteristics are different in the two directions as a result of the use of different frequencies.
UL/DL asymmetry	It is possible to dynamically change the UL and DL capacity ratio to match demand.	UL/DL capacity is determined by frequency allocation set out by the regulatory authorities. It is therefore not possible to make dynamic changes to match capacity. Regulatory changes would normally be required and capacity is normally allocated so that it is the same in either direction.
Guard period/ guard band	Guard period required to ensure uplink and downlink transmissions do not clash. Large guard period will limit capacity. Larger guard period normally required if distances are increased to accommodate larger propagation times.	Guard band required to provide sufficient isolation between uplink and downlink. Large guard band does not impact capacity.
Discontinuous transmission	Discontinuous transmission is required to allow both uplink and downlink transmissions. This can degrade the performance of the RF power amplifier in the transmitter.	Continuous transmission is required.
Cross slot interference	Base stations need to be synchronized with respect to the uplink and downlink transmission times. If neighboring base stations use different uplink and downlink assignments and share the same channel, then interference may occur between cells.	Not applicable

channels (paired spectrum) that are separated by a guard band of a number of vacant radio frequency (RF) channels for interference avoidance. Figure 10.12a illustrates a typical spectrum allocation in which user i is allocated a pair of channels Ui and Di with bandwidths WU and WD. The frequency offset, WO, used to separate the pair of channels should be large enough for the user terminal to avoid self-interference among the links because both links are simultaneously active.

For TDD, the UL and DL transmissions operate in the same band but alternate in the time domain. Capacity can be allocated more flexibly than with FDD. It

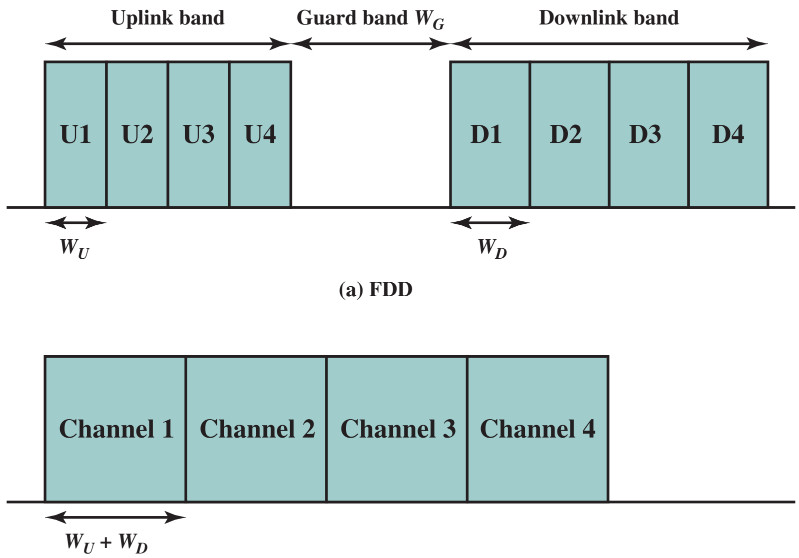


Figure 10.12 Spectrum Allocation for FDD and TDD

is a simple matter of changing the proportion of time devoted to UL and DL within a given channel.

Carrier Aggregation **Carrier aggregation** is used in LTE-Advanced in order to increase the bandwidth, and thereby increase the bit rates. Since it is important to keep backward compatibility with LTE the aggregation is of LTE carriers. Carrier aggregation can be used for both FDD and TDD. Each aggregated carrier is referred to as a component carrier, CC. The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15, or 20 MHz and a maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz. In FDD, the number of aggregated carriers can be different in DL and UL. However, the number of UL component carriers is always equal to or lower than the number of DL component carriers. The individual component carriers can also be of different bandwidths. When TDD is used the number of CCs and the bandwidth of each CC are the same for DL and UL.

Figure 10.13a illustrates how three carriers, each of which is suitable for a 3G station, are aggregated to form a wider bandwidth suitable for a 4G station. As Figure 10.13b suggests, there are three approaches used in LTE-Advanced for aggregation:

- **Intra-band contiguous:** This is the easiest form of LTE carrier aggregation to implement. Here, the carriers are adjacent to each other. The aggregated channel can be considered by the terminal as a single enlarged channel from the RF viewpoint. In this instance, only one transceiver is required within the subscriber station. The drawback of this method is the need to have a contiguous spectrum band allocation.

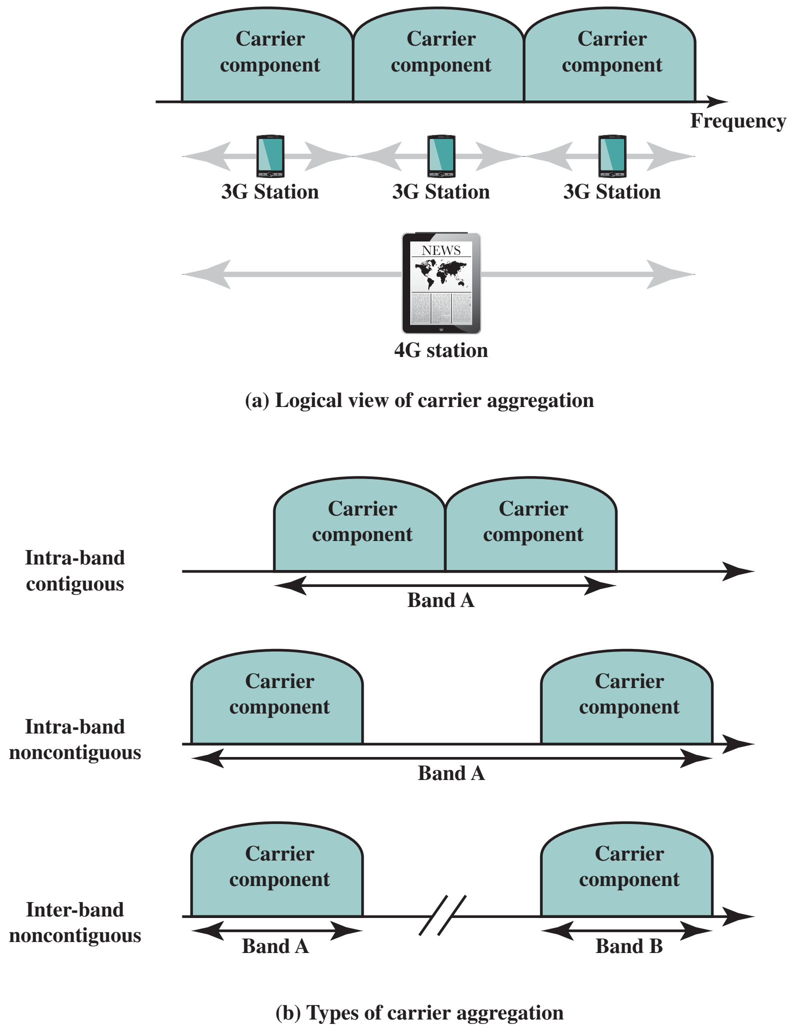


Figure 10.13 Carrier Aggregation

- **Intra-band noncontiguous:** Multiple CCs belonging to the same band are used in a noncontiguous manner. In this approach, the multicarrier signal cannot be treated as a single signal and therefore multiple transceivers are required. This adds significant complexity, particularly to the UE where space, power, and cost are prime considerations. This approach is likely to be used in countries where spectrum allocation is noncontiguous within a single band or when the middle carriers are in use by other subscribers.
- **Inter-band noncontiguous:** This form of carrier aggregation uses different bands. It will be of particular use because of the fragmentation of bands—some of which are only 10 MHz wide. For the UE it requires the use of multiple transceivers within the single item, with the usual impact on cost, performance, and power.

10.4 RECOMMENDED READING

[BERT94] and [ANDE95] are instructive surveys of cellular wireless propagation effects. [TANT98] contains reprints of numerous important papers dealing with CDMA in cellular networks. [OJAN98] provides an overview of key technical design considerations for 3G systems. Another useful survey is [ZENG00].

Worthwhile introductions to LTE-Advanced include [FREN13], [BAKE12], [PARK11], and [GHOS10]. [CHAN06] explores the use of FDD and TDD in 4G networks. [IWAM10] provides an overview of LTE-Advanced carrier aggregation. [BAI12] discusses LTE-Advanced modem design issues.

ANDE95 Anderson, J.; Rappaport, T.; and Yoshida, S. "Propagation Measurements and Models for Wireless Communications Channels." *IEEE Communications Magazine*, January 1995.

BAI12 Bai, D., et al. "LTE-Advanced Modem Design: Challenges and Perspectives." *IEEE Communications Magazine*, February 2012.

BAKE12 Baker, M. "From LTE-Advanced to the Future." *IEEE Communications Magazine*, February 2012.

BERT94 Bertoni, H.; Honcharenko, W.; Maciel, L.; and Xia, H. "UHF Propagation Prediction for Wireless Personal Communications." *Proceedings of the IEEE*, September 1994.

CHAN06 Chan, P., et al. "The Evolution Path of 4G Networks: FDD or TDD?" *IEEE Communications Magazine*, December 2006.

FREN13 Frenzel, L. "An Introduction to LTE-Advanced: The Real 4G." *Electronic Design*, February 2013.

GHOS10 Ghosh, A., et al. "LTE-Advanced: Next-Generation Wireless Broadband Technology." *IEEE Wireless Communications*, June 2010.

IWAM10 Iwamura, M., et al. "Carrier Aggregation Framework in 3GPP LTE-Advanced." *IEEE Communications Magazine*, August 2010.

OJAN98 Ojanpera, T., and Prasad, G. "An Overview of Air Interface Multiple Access for IMT-2000/UMTS." *IEEE Communications Magazine*, September 1998.

PARK11 Parkvall, S.; Furuskar, A.; and Dahlman, E. "Evolution of LTE toward IMT-Advanced." *IEEE Communications Magazine*, February 2011.

TANT98 Tantaratana, S., and Ahmed, K., eds. *Wireless Applications of Spread Spectrum Systems: Selected Readings*. Piscataway, NJ: IEEE Press, 1998.

ZENG00 Zeng, M.; Annamalai, A.; and Bhargava, V. "Harmonization of Global Third-generation Mobile Systems." *IEEE Communications Magazine*, December 2000.

10.5 KEY TERMS, REVIEW QUESTIONS, AND PROBLEMS

Key Terms

adaptive equalization	first-generation (1G) network	packet data network gateway (PGW)
Advanced Mobile Phone Service (AMPS)	forward error correction	reflection
base station	fourth-generation (4G) network	relay node (RN)
carrier aggregation	frequency diversity	relaying
cellular network	frequency-division duplex (FDD)	reuse factor
code division multiple access (CDMA)	frequency reuse	scattering
diffraction	handoff	second-generation (2G) network
diversity	home subscriber server (HSS)	selective fading
donor eNodeB	long-term evolution (LTE)	serving gateway (SGW)
evolved NodeB (eNodeB)	LTE-Advanced	slow fading
evolved packet core (EPC)	mobile radio	space diversity
fading	mobility management entity (MME)	third-generation (3G) network
fast fading		time-division duplex (TDD)
femtocells		
flat fading		

Review Questions

10.1 What geometric shape is used in cellular system design?

10.2 What is the principle of frequency reuse in the context of a cellular network?

10.3 List five ways of increasing the capacity of a cellular system.

10.4 Explain the paging function of a cellular system.

10.5 What is fading?

10.6 What is the difference between diffraction and scattering?

10.7 What is the difference between fast and slow fading?

10.8 What is the difference between flat and selective fading?

10.9 What are the key differences between first- and second-generation cellular systems?

10.10 What are some key characteristics that distinguish third-generation cellular systems from second-generation cellular systems?

Problems

10.1 The first-generation AMPS system used a frequency allotment of K frequencies and a basic cell pattern of $N = 7$. What is the maximum number of frequency bands per cell?

10.2 Consider four different cellular systems that share the following characteristics. The frequency bands are 825 to 845 MHz for mobile unit transmission and 870 to 890 MHz for base station transmission. A duplex circuit consists of one 30-kHz channel in each direction. The systems are distinguished by the reuse factor, which is 4, 7, 12, and 19, respectively.

a. Suppose that in each of the systems, the cluster of cells (4, 7, 12, 19) is duplicated 16 times. Find the number of simultaneous communications that can be supported by each system.
b. Find the number of simultaneous communications that can be supported by a single cell in each system.
c. What is the area covered, in cells, by each system?
d. Suppose the cell size is the same in all four systems and a fixed area of 100 cells is covered by each system. Find the number of simultaneous communications that can be supported by each system.

10.3 Describe a sequence of events similar to that of Figure10.6 for

a. a call from a mobile unit to a fixed subscriber
b. a call from a fixed subscriber to a mobile unit

10.4 An analog cellular system has a total of 33 MHz of bandwidth and uses two 25-kHz simplex (one-way) channels to provide full-duplex voice and control channels.

a. What is the number of channels available per cell for a frequency reuse factor of (1) 4 cells, (2) 7 cells, and (3) 12 cells?
b. Assume that 1 MHz is dedicated to control channels but that only one control channel is needed per cell. Determine a reasonable distribution of control channels and voice channels in each cell for the three frequency reuse factors of part (a).

10.5 A cellular system uses FDMA with a spectrum allocation of 12.5 MHz in each direction, a guard band at the edge of the allocated spectrum of 10 kHz, and a channel bandwidth of 30 kHz. What is the number of available channels?

10.6 For a cellular system, FDMA spectral efficiency is defined as $\eta_a = \dfrac{B_c N_T}{B_w}$ where

B_c = channel bandwidth
B_w = total bandwidth in one direction
N_T = total number of voice channels in the covered area

What is an upper bound on η_a?